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The International Seismic Monitoring System needs the following three refinements: i) regional adjustments of travel-time curves and amplitude-distance relations; ii) surfase wave detection; and iii) location of small events. We have investigated anomalous structures of Bolivia, Chile and Colombia-Venezuela and established models of seismic wave velocity as a function of depth; we have modelled the transmission of Love and Rayleigh waves in Bolivia and northern Chile; our station LPAZ of the Global Telemetered Seismic Network, our group of high gain French stations and our files of seismograms since 1913 make La Paz a National Data Center in central South America, authorized by the Bolivian Government. This has been complemented by: i) participating with several foreign teams of seismologists, installing their equipment in Bolivia; and ii) revising the history of seismicity of Bolivia and identifying six seismogenic zones, corresponding to the structural complexity.

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# SEISMIC WAVE PROPAGATION IN SOUTH AMERICA

## STATEMENT OF WORK

1. Time-distance curves for P waves (which give the velocity structure within the earth, independently of models) recorded at La Paz for earthquakes in the region of Venezuela and from earthquakes of intermediate depth in the region of Colombia show considerable scatter and need much further investigation.

2. We propose to apply particle motion analysis, Fourier analysis and attribute analysis to the P and subsequent wavetrains of earthquakes and explosions recorded at our Bolivian stations.

3. We propose to use a local crustal and upper mantle model to locate earthquakes in the region of Bolivia and to try to allow for at least one dipping layer.

4. Although the Nazca plate has three distinct dips under Bolivia, we can model, by the finite element method, the propagation of Rayleigh and Love waves, including $R_g$ and $L_g$ waves, across the dipping sections.

5. With the new Global Telemetered Seismic Network station and the new French high-gain digital seismometers arriving soon, we propose to continue the tomographic work on the crustal and upper mantle structure of northern Bolivia.

6. We propose to study and apply further the waveform correlation method for identifying quarry and mine explosions.

7. Studies of the focal mechanism, depth, magnitude and seismic moment of earthquakes 20 to 100 km ENE of Cochabamba need to be continued and extended to other regions.

8. The magnitudes of the larger earthquakes in southern Bolivia appear to have been overestimated and the intensities, attenuation and risk there, and possibly in other parts of Bolivia, need revision.

## STATUS OF RESEARCH EFFORT

Along the two and a half years of investigation, we have concentrated on points 1,2,4,6,8 of the Statement of Work.

### The International Seismic Monitoring System

In the preparation of the International Monitoring System required for the Comprehensive Test Ban Treaty (CTBT), Harjes (1995) has recalled three principal lessons: 1. The International Seismic Monitoring System (ISMS) needs to be calibrated with respect to

travel-time curves and amplitude-distance relations. 2. Provision of adequate surface wave detection and reporting should be included in the design of the ISMS. 3. To detect and locate small events, the observation of the seismic wavefield at regional distances is essential, Sykes (1995). Kennett (1993) has remarked that the seismic source imposes a distinctive pattern on the radiated seismic wavefield, but this pattern is profoundly modified on passing through an irregular region.

The crustally guided wave Lg is useful in the discrimination of seismic sources and has been used intensively, but it can vary significantly from a single source.

On-site inspection requires the location of events, whether earthquakes or explosions, to plus or minus 5 km, for an inspection area of 100 $km^2$. It is difficult in north and west South America, on account of irregularities occurring in that area. So it is urgent to get a better knowledge of that region, if we want to avoid errors in the location of either earthquakes or explosions producing waves traversing that zone. Eisenberg and his coworkers (1989) located with local seismograph stations aftershocks of the 1985 Chile earthquake and some 1981 earthquakes; they found that almost 10 % of the NEIC locations of these earthquakes differed by more than 65 km from the locations found from the local stations.

Another example of how much the locations made by different agencies may differ in that region:
Earthquake of July 30, 1995, magnitude 7.8, just north of Antofagasta, felt in La Paz:

| | |
|---|---|
| European Mediterranean Seismic Center | - 23.29° S, 70.36° W |
| US Geological Survey, NEIC | - 23.4° S, 70.2° W |
| University of Chile in Santiago | - 23.445°S, 70.477°W |
| OSC, using first motion and S-P | - 24.74° S, 69.62° W |
| OSC, using SP stations near La Paz | - 24.77° S, 71.343°W |

For a CTBT it is necessary to avoid such discrepancies, especially considering the number of earthquakes of magnitude similar to that of possible nuclear explosions; about 21,000 earthquakes per year happen in the world of magnitude 3.5; such magnitude may be reached by a 10 kt explosion decoupled in salt (Conferencia de Desarme, 1994a; 1994b).

Fujita and coworkers (1981) and Abers (1992) pointed out that epicenters in regions of subduction based on teleseismic recordings are biased landward away from the trench by several tens of km; rays travelling landward from the trench traverse a portion of the subducting slab and have negative residuals of 1.0 to 1.5 s for 100 km of slab traversed; high velocities down the slab from the hypocenter drag its location in their direction.

Another example: Approximately 200 km WNW of Bogota, Colombia, 5.0°S, 75.7°W, depth 130 km at 21h 43m 32s (USGS, NEIC).

Its distance to our GTSN station LPAZ was 22.4° and its azimuth 340°. In this case: a) respect to the travel-time tables of Kennett (1991, 1995) the P wave was 4s late at LPAZ. We have to remark that Kennett's tables are based on a radial velocity model with a crust and mantle representative of continental regions regularly stratified (the values of P are approximately 0.7 s slower than those of Herrin (1968) and approximately 1.8 s faster than those of Jeffreys and Bullen (1948). We assume that the 4 s delay at LPAZ is due to partially molten material above the subducting Nazca plate and to the 60-70 km thick crust under LPAZ. That earthquake was of intermediate depth; nevertheless S was difficult to find (cf. Jeffreys and Bullen, 1948, p. 5). We may remark that Lg waves appear to be visible in spite of being produced by earthquakes deeper than normal (as usually happens for that azimuth); their velocity is 3.51 km/s (Ewing et al., 1957); the surface (phase) velocity of ScP and PcS at a distance of 22 degrees is 3.39 km/s (Richter, 1958, p. 682) and thus these phases interfere with the Lg wave train.

TABLE 1
MODEL OF THE CORDILLERA REAL TO A DEPTH OF 470 KM (fig. 1)

| Layer thickness km | Compressional velocity km/s | Shear velocity km/s | Density $g/cm^3$ | Poisson's ratio | Quality factor Q |
|---|---|---|---|---|---|
| 4.0 | 5.00 | 2.97 | 2.70 | 0.227 | 30 |
| 7.0 | 5.60 | 3.33 | 2.70 | 0.227 | 40 |
| 13.0 | 6.00 | 3.51 | 2.75 | 0.240 | 50 |
| 8.0 | 6.10 | 3.52 | 2.75 | 0.250 | 60 |
| 15.0 | 6.20 | 3.58 | 2.75 | 0.250 | 80 |
| 6.0 | 6.50 | 3.75 | 2.83 | 0.251 | 100 |
| 6.0 | 5.90 | 3.41 | 2.83 | 0.249 | 50 |
| 6.0 | 6.50 | 3.75 | 2.95 | 0.251 | 200 |
| 10.0 | 8.10 | 4.74 | 3.24 | 0.240 | 400 |
| 10.0 | 8.10 | 4.74 | 3.30 | 0.240 | 400 |
| 10.0 | 8.10 | 4.74 | 3.35 | 0.240 | 400 |
| 14.0 | 8.10 | 4.74 | 3.36 | 0.240 | 400 |
| 15.0 | 8.10 | 4.74 | 3.37 | 0.240 | 400 |
| 20.0 | 7.85 | 4.46 | 3.38 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.39 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.40 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.41 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.43 | 0.262 | 80 |
| 26.0 | 8.62 | 4.54 | 3.44 | 0.308 | 143 |
| 26.0 | 8.69 | 4.58 | 3.46 | 0.308 | 143 |
| 34.0 | 8.77 | 4.62 | 3.47 | 0.308 | 143 |
| 34.0 | 8.87 | 4.67 | 3.49 | 0.308 | 143 |
| 40.0 | 8.97 | 4.67 | 3.52 | 0.307 | 143 |
| 40.0 | 9.08 | 4.79 | 3.54 | 0.307 | 143 |
| 50.0 | 9.60 | 5.09 | 3.80 | 0.304 | 143 |

We have also considered earthquakes in Brazil at distances of from 30° to 40° from La Paz. We have fitted splines (Curtis and Shimshoni, 1970; Press et al., 1986, p. 86) to Kennett's travel-time data, and we tried continuing his P time-distance curve from 30° to 40° by fitting polinomials, but the earthquakes were too small and the results too scattered to tell us much about the earth's mantle underneath western Brazil.

The Andean Cordillera in Bolivia is divided into Cordillera Occidental at the border with Chile and the Cordillera Oriental (called Cordillera Real in its northern part) separated by the Lake Titicaca and the Altiplano. In central Bolivia, on account of the Arica "elbow" of the western South American coastline, the Nazca plate is forced to spread and change its strike from approximately NW-SE to approximately N-S (Omarini et al., 1991; Dorbath et al., 1993; Baby et al., 1993; Lamb et al., 1993; Riccardi, 1988, p. 34; Scheuer et al., 1994). This causes extreme complexity in the structure of the Cordillera Oriental and the Subandean zone in central Bolivia (18°S, 66°W).

The Cordillera Oriental runs southeast, and then southsoutheast from the cordillera of Arcopongo, just north of Cochabamba (17° 24'S, 66° 09'W; Ahlfeld, 1972, p. 20).

Vega and Buforn (1991) and Dewey and Lamb (1992) have investigated the focal mechanisms of earthquakes in central Bolivia.

There are two main bands of associated deep earthquakes, one from 06.5° S, 71.5° W, to 11.5° S, 71.0° W, in western Brazil and southern Peru, and the other from 19.0° S, 63.5° W to 28.5° S, 63.0° W in southern Bolivia and northern Argentina (Okal et al., 1994).

On June 9, 1994, a deep event, that was felt as far away as Canada, occurred between these zones (Harvard centroid time and location, 00:33:44.4, 13.81° S, 67.20° W, depth 657.4 km; Mw 8.3). It has been the subject of a symposium in two sessions plus presentation of posters in the AGU Fall Meeting 1994 (AGU, 1994). Within our project Angel Vega (1994, p. 39-55) has studied that earthquake.

TABLE 2
TOP 20 KM OF THE MODEL OF THE ALTIPLANO REGION

| Layer thickness km | Compressional velocity km/s | Shear velocity km/s | Density $g/cm^3$ | Poisson's ratio | Quality factor Q |
|---|---|---|---|---|---|
| 7.0 | 4.50 | 2.70 | 2.50 | 0.219 | 20 |
| 7.0 | 5.00 | 2.97 | 2.70 | 0.227 | 30 |
| 6.0 | 5.40 | 3.21 | 2.70 | 0.227 | 40 |

In the region of the low angle Main Andean Thrust, between the

Cordillera Real and the Subandean Ranges in northern Bolivia (15°.7 S, 67°.5 W), there is overlap of approximately 230 km of Neogene age (Roeder, 1988; cf. Allmendinger et al., 1990, for overlap in Argentina at latitude 30°S). The Cordillera Real fault system, at the southwestern border of the Cordillera Real (16°.6 S, 67°.8 W), marks a subvertical boundary, dipping slightly to the southwest from the surface down to a depth of 140 km; it separates two strongly contrasting velocity units (Dorbath et al., 1993). The depth to the Moho beneath the Altiplano is approximately 70 km and, beneath the Cordillera Real, is approximately 60 km (James, 1971; Ocola et al., 1971; Wigger et al., 1991; 1994; Beck, personal communication). The Brazilian Shield under the Eastern Cordillera appears to be partially molten (Wigger et al., 1994; Giese, 1994); measurements of primordial mantle $^3He$ (Hoke et al., 1993; 1994) indicate active mantle melting under the Cordillera Real.

Surprisingly, with 230 km of thrusting, there is normal faulting in the western part of the Cordillera Real (Dorbath et al., 1993). The explanation appears to be that the Brazilian Shield is causing a vertical gravitational stress with a corresponding horizontal extension. Schwartz (1988) has offered this explanation for the spectacular normal faulting (e.g. 3 m in the Ancash earthquake of 1946) in the Cordillera Blanca Fault Zone in the northern Peruvian Andes (cf. Sébrier et al., 1985; 1988; Suárez et al., 1983).

For the regions of the Cordillera Real and the Altiplano, the variation with depth of the displacement of the Love and Rayleigh modes is normalized (see figs. 2, 3, 4) such that the energy the mode transports is proportional to the product of its wave number, its frequency and the square of its amplitude (Lysmer and Drake, 1972). The analysis of the finite element model gives the phase changes of the Love and Rayleigh modes of diferent frequencies across the irregular part of the model, and, hence, the average phase velocities of these modes within the model. Results for the fundamental Love mode and for the fundamental Rayleigh mode at a period of 2 s are tabulated in table 3. The analysis of the finite element model also gives the changes of amplitude of the modes across the model and the percentages of energy either retained in the modes or reflected and scattered into other modes. The changes of amplitude of the fundamental Love mode and of the fundamental Rayleigh mode at a period of 2 s are tabulated in table 4. The surface amplitude of the fundamental Love mode actually increases on passing from the Altiplano to the Cordillera Real. Because 91.69 percent of the energy of the fundamental Love mode at a period of 2 s is transmitted from the Altiplano to the Cordillera Real, 8.31 percent of the energy of this mode goes into reflected and forward scattered modes. Energy in the fundamental Love mode below the surface of the Altiplano has passed to the surface in the fundamental Love mode of the Cordillera Real to give the increase of surface amplitude. Because 98.60 percent of the energy of the fundamental Rayleigh mode passes from the Altiplano to the Cordillera Real; only 1.40 percent of the energy of this mode is

reflected and scattered. The results in tables 3 and 4 were obtained without allowance for absorption, in order to make sure that the energies of the incidental fundamental Love and Rayleigh modes exactly balanced the sums of all of the energies of the reflected and transmitted modes.

A two-dimensional section of length 62 km of this deforming region, along a part of the SW-NE profile examined by Dorbath and her coworkers (1993), from the Altiplano to the Cordillera Real, northeast from 17° S, 68° W and just south of La Paz, Bolivia, has now been modelled by the finite element method in the frequency domain, and the propagation of Love and Rayleigh waves of short period has been analysed. The horizontally layered structures representing the regions of the Cordillera Real and the Altiplano are shown in tables 1 and 2 (Wigger et al., 1991; 1994; Dorbath et al., 1993); values of Poisson's ratio and the properties of the earth's mantle were taken from global models (Dziewonski and Anderson, 1981; Dziewonski et al., 1975; Morelli and Dziewonski, 1993; Kennett, 1991; 1995). The thicknesses and material properties of the intermediate elements of the finite element model were averaged from the thicknesses and material properties of the layers of the end structures.

TABLE 3
PHASE VELOCITIES FROM THE ALTIPLANO TO THE CORDILLERA REAL

| Phase velocity km/s | Altiplano | Transition zone | Cordillera Real |
|---|---|---|---|
| Love wave | 2.7337 | 2.9441 | 3.0717 |
| Rayleigh wave | 2.4805 | 2.6905 | 2.7590 |

TABLE 4
DISPLACEMENTS FROM THE ALTIPLANO TO THE CORDILLERA REAL

| Surface displacement | | Altiplano | Cordillera Real |
|---|---|---|---|
| Love wave | | 0.1119 | 0.1176 |
| Rayleigh wave: | horizontal | 0.1104 | 0.0998 |
| | vertical | 0.1620 | 0.1478 |

In western Bolivia, southeast of Lake Titicaca, there is left-hand strike-slip on the Laurani fault (Dorbath et al., 1993), but in central Bolivia, southeast of Cochabamba, there is right-hand strike-slip on, for example, the north-south Aiquile fault (18° S, 65°15'W; Vega and Buforn, 1991; Dewey and Lamb, 1992). The brief explanation of this difference is that the pole of rotation of the Nazca-South America plate convergence is at 56° N, 94° W (Fowler, 1990, p. 13; Gordon, 1995); the resulting convergence at Arica (18°29'S, 70°20'W) is 8.24 cm/y with an azimuth of 77°; the

TABLE 5
MODEL OF IQUIQUE TO A DEPTH OF 220 KM

| Layer thickness km | Compressional velocity km/s | Shear velocity km/s | Density $g/cm^3$ | Poisson's ratio | Quality factor Q |
|---|---|---|---|---|---|
| 0.3 | 3.80 | 2.28 | 2.35 | 0.219 | 20 |
| 1.5 | 5.50 | 3.30 | 2.63 | 0.219 | 20 |
| 1.8 | 5.90 | 3.51 | 2.68 | 0.227 | 20 |
| 10.4 | 6.30 | 3.74 | 2.75 | 0.227 | 30 |
| 6.0 | 6.80 | 3.98 | 2.83 | 0.240 | 40 |
| 8.8 | 7.00 | 4.09 | 2.86 | 0.240 | 60 |
| 13.6 | 7.40 | 4.27 | 3.14 | 0.250 | 80 |
| 9.0 | 8.20 | 4.80 | 3.30 | 0.240 | 400 |
| 22.6 | 8.02 | 4.69 | 3.35 | 0.240 | 400 |
| 23.0 | 8.02 | 4.69 | 3.36 | 0.240 | 400 |
| 23.0 | 8.02 | 4.69 | 3.37 | 0.240 | 400 |
| 20.0 | 7.85 | 4.46 | 3.38 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.39 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.40 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.41 | 0.262 | 80 |
| 20.0 | 7.85 | 4.46 | 3.43 | 0.262 | 80 |

resulting principal compressive stress from the Nazca plate on the Andes, striking NW-SE in the region of the Laurani fault, is towards the right along the strike of the fault and this causes left-hand strike-slip; in the region of the Aiquile fault, the strike of the Andes is N-S; the resulting principal compressive stress is towards the left along the strike of the fault and this causes right-hand strike-slip.

During the period of this report, a large amount of seismic investigation has taken place into the irregular earth structure in the region of the Andes in Bolivia (Beck et al., 1994a; 1994b; Soler, personal communication; Okal et al., 1994). Absorption of Lg in the Western Cordillera is probably connected with the high heat flow (80 $mW/m^2$) and the volcanism there since the beginning of the Neogene; heat flow in the Cordillera Real is less (60$mW/m^2$; Omarini et al., 1991; Giese, 1994).

We have observed at La Paz that Lg waves of periods of 1.5 and 1.6 s arrive from the Caribbean Sea, north of northwestern Colombia, but, apart from absorption in the Western Cordillera and in the Altiplano, they appear not to arrive from the Chile trench to the west of La Paz. We have constructed models of the structure below Iquique, Chile (20° 13'S, 70° 10'W), and of the structure below the oceanic trench off the coast from Iquique (tables 5 and 6; Wigger et al., 1994; Dziewonski et al., 1975; Dziewonski and Anderson, 1981; Kennett, 1991; 1995; Drake, 1989).

TABLE 6
MODEL OF IQUIQUE TRENCH TO A DEPTH OF 220 KM

| Layer thickness km | Compressional velocity km/s | Shear velocity km/s | Density $g/cm^3$ | Poisson's ratio | Quality factor Q |
|---|---|---|---|---|---|
| 6.0 | 1.52 | 0.001 | 1.03 | 0.500 | 500 |
| 1.0 | 2.15 | 0.50 | 1.80 | 0.471 | 20 |
| 1.0 | 4.70 | 2.50 | 2.50 | 0.303 | 40 |
| 5.0 | 6.80 | 3.80 | 2.90 | 0.273 | 60 |
| 20.0 | 8.20 | 4.70 | 3.31 | 0.255 | 400 |
| 27.0 | 8.20 | 4.70 | 3.33 | 0.255 | 400 |
| 20.0 | 7.90 | 4.34 | 3.34 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.36 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.37 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.38 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.39 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.40 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.41 | 0.284 | 80 |
| 20.0 | 7.90 | 4.34 | 3.43 | 0.284 | 80 |

The variation of displacement with depth of the fundamental Love modes of periods 0.7 s, 1.5 s, 5.0 s and 10.0 s for the model of the structure below Iquique is shown in fig. 2; the modes are normalized so that the energy they transmit is proportional to the product of their angular frequency and wavenumber (Lysmer and Drake, 1972). The variation of displacement with depth of the fundamental Love modes of these periods for the model of the structure below the oceanic trench off the coast of Iquique cannot be conveniently shown, because the modes of the shorter periods travel practically entirely in the sediments in the trench (assumed to be of thickness 1 km) while the mode of period 10 s travels predominantly in the low velocity zone at a depth of approximately 110 km (Drake and Bolt, 1980). The phase velocities of these modes in the model of the structure below Iquique are between 3.06 and 4.14 km/s; the phase velocities of the Love modes of the shorter period (1.9 to 3.7 s) in the model of the structure below the trench are between 0.51 s and 0.57 s. There is no need to analyse a two-dimensional finite element model to see that there is practically no coupling between the Love modes below the oceanic trench and the modes below Iquique. In 1957, Ewing, Jardetzky and Press (p. 219) noted that as little as 2° of intervening ocean is enough to eliminate the Lg phase entirely. At present we are considering the relation between the Love and Rayleigh modes of short period in our various models and the Lg and the Rg phases (Press and Ewing, 1952; Nuttli, 1986).

The investigations made after 6 months of recording in the temporary project Lithoscope Bolivia, confirm the zone complexity either considering surface geology and tectonics (see fig. 5) or through the results of tomography obtained by Aldunate (1995) for

the wave velocity anomalies, as it may be seen in fig. 6. In that program 41 short-period seismographs were used, 34 of them in Bolivia, the others in Chile. 120 Teleseismic events with initial P or PKP phase quite clear were considered. A similar result is being obtained by Frontanilla, considering local or regional earthquakes.

After all that, the results of ancient work of the Carnegie Institution are not so surprising as they could appear: In 1957 they failed to record explosions of 60 tons at Toquepala, Peru, beyond 230 km across the mountains and the Altiplano, although from explosions both at this mine and at the Chuquicamata mine, Chile, they successfully identified the Mohorovicic discontinuity in Peru and Chile for wave paths running along the western flank of the plateau (Aldrich et al., 1958; 1959). In 1968 a larger group used explosions of one ton in lakes 850 km apart, in southern Peru through central Bolivia, hoping to obtain a reversed profile, but they failed to record any seismic energy from the mantle in Peru and obtained only 200 km of single profile in Bolivia (Department of Terrestrial Magnetism staff et al., 1970).

Minaya and her coworkers (1989), Ayala and his coworkers (1993) and Ayala (1994) have observed that, at the WWSSN station at La Paz, Bolivia (LPB; 16° 32'S, 68° 06'W; 3292 m) there is much greater attenuation of Lg waves of periods of approximately 1.2 s from the Western Cordillera to the west of La Paz than from the Brazilian and Guyana shields to the east. Ayala (1994) gives different formulas for Lg equivalent body waves magnitude and different exponential decays of the maximum amplitude of the Lg waves with distance (0.2/degree from the west, and 0.09/degree from the east). The Cordillera Occidental appears to be highly attenuating at these short periods. We suspect that the 20 km thickness of sediments beneath the Altiplano (Dorbath et al., 1993) also strongly absorbs seismic waves of short period.

Isacks (1988), Ayala (1991) and Cahill and Isacks (1992) have mapped the warping of the Nazca plate under South America. It appears to be flat in southern Peru. At 15° S there is a sharp flexure of the plate and its dip under Bolivia is approximately 30°. There is a gradual transition southward to nearly horizontal dip in the region from the 28° S to 32° S beneath the western Argentina. At 33° S there is another sharp flexure of the plate to a dip of approximately 30°.

The Andean chain originated in two major orogenic cycles of the Phanerozoic, the Late Precambrian-Paleozoic Preandean Cycle and the Mesozoic-Cenozoic Andean Cycle (Omarini et al., 1991). During the Preandean Cycle, huge depocenters developed successively further westward, from the Subandean Ranges in Bolivia and northern Argentina to the Longitudinal Valley and Coastal Cordillera in Chile (Castaños and Rodrigo, 1978, p. 41; Instituto Geográfico Militar, 1985, p. 166; Ahlfeld, 1972, p. 40). During the Andean

Cycle, four magmatic arc systems developed successively eastward (Dorbath et al., 1993). In the region of Main Andean Thrust, between the Eastern Cordillera and the Subandean Ranges in northern Bolivia, there is overlap of approximately 230 km of Neogene age (Roeder, 1988; cf. Allmendinger et al., 1990). The Main Andean Thrust appears to be steeply dipping and the Cordillera Real fault system, at the southwestern border of the Cordillera Real, marks a subvertical boundary, dipping slightly to the southwest, which, from the surface down to a depth of 140 km, separates two strongly contrasting velocity units.

Whitman and his coworkers (1992) have noted that for a portable seismic network deployed in Jujuy Province (24° S, 65° W), Argentina, P and S short period waves propagate beneath the plateau much more efficiently from the north and northwest than from the west and south; likewise Sn phases from regional crustal earthquakes in the Subandean foreland fold-thrust belt to the north propagate efficiently to the Jujuy network, while Sn is not observed from foreland earthquakes located at similar distances to the south of the nerwork.

Colombia and Venezuela

For Colombia, we have constructed velocity models of the regions below Quibdó (5° 42'N, 76°40'W; Flüh et al., 1981), below Barranquilla (10° 59'N, 74°48'W) and below the Caribbean Sea, using the amplitudes of Love and Rayleigh waves. With the purpose of comparison, similar models have been constructed for the Coastal Cordillera, east of Iquique, below the Cordillera Occidental, below the Altiplano, below La Paz, and below the Cordillera Oriental. At present we continue analyzing by the finite element method the propagation of Love and Rayleigh waves across these regions, considering also Lg and Rg phases.

We have studied the structure of Colombia by analyzing its seismicity and correlating it with tectonic and geological characteristics, to gain insight of lithospheric plate dynamics in the region; the end product will be the knowledge of seismic wave transmission.

That correlation may be complex when three or more plates meet in a region and it is paticularly complex in the southwest corner of the Caribbean plate in Colombia, where the South American plate, the Nazca plate and the Andean block (apparently detached from South American plate, Ramírez, 1977; Pennington, 1981a; 1981b) meet the Caribbean plate (fig. 7); moreover the direction of South American plate related to the Caribbean is oblicuous to the direction of Nazca plate movement.

This may be crucial to interpret the regional plate dynamics. Most investigastors in their studies focusing the northern and eastern Caribbean, include, as a complementary subject, the southwestern

Caribbean region; then they follow the opinion of Pennington et al., (1979), considering, either explicitly or implicitly, the Bucaramanga seismic nest (6.8°N, 73.1° W, depth around 158 km) as the end of the Caribbean subducted slab. That nest is located in a tectonically tormented zone in the southern apex of Maracaibo triangle (fig. 7), that is to say, in the bifurcation of faults Santa Rosa-Bucaramanga left-hand strike-slip SE-NW and Boconó right-hand strike slip SW-NE. The Oca-Ancón is another fault system right-hand strike-slip, cutting the Maracaibo block, as a continuation of El Pilar-San Sebastián E-W system (Pennington, 1981a; 1981b; Beltrán, 1993; Coral-Gómez and Mendoza, 1993).

A recent estimation of plate motions and boundaries, with the assumption that "plates appear to an excellent approximation to be rigid" (Gordon, 1995), suggests that there is some thrust superposed on the right-hand strike-slip motion of the Boconó-Mérida fault system near Mérida in western Venezuela (8° 36'N, 71° 08'W).

We have examined the hypothesis of the Bucaramanga nest pertaining to the Caribbean subducted plate, looking for the characteristic continuous band of seismicity along subducted plates at shallow and intermediate depth, below the top plate. We could not find such a continuous band, especially after excluding several foci of entirely dubious determination (See fig. 8). On the contrary, since the Pacific coast the northernmost part of Nazca plate reveals itself through the characteristic band of seismicity dipping westnorthwest (with hypocenters what could appear belonging to the Caribbean plate) until the Bucaramanga nest (See fig. 8). This explains partly the good recording of Lg in Bolivia originated in Bucaramanga intermediate depth foci, since the slab offers a good S wave path to the surface.

Looking to the absolute plate movements, we summarize: The Nazca plate, with superposed Andean block, from the west, and the South American plate, from the east, squeeze the wedge of Maracaibo block near Bucaramanga; this block slides to the north, explaining the convexity into the Caribbean, but distending the central part of the base of the Maracaibo triangle in the back basin of lake Maracaibo. The drag of the South American plate and the immobility of the Caribbean in the other side, have detached that convexity along the Oca-Ancón fault, dividing the Maracaibo block into two microplates. The southwestern part of the Caribbean with the obduction of South America, is deformed, being the main aspects of deformation the elevation of Santa Marta massif during the Plio-Quaternary and the contortion of Panama isthmus. The northernmost part of Nazca plate moves northnorthwest (though slower than the rest of the plate, because for the same rotation the radius is shorter); it is subducted beneath Colombia until a depth of about 200 km, with a lower seismic activity, except in the Bucaramanga nest, where tectonic complexity, with causes suggested above, explain the permanent unrest.

## Seismicity

Instrumental data is obtained and analyzed daily in the Bolivian network (fig. 9).

The study of seismic activity is not only useful for the prevention of seismic risk, but moreover it is a contribution to the knowledge of earth structure.

A main objective in the study of the seismicity of Bolivia has been to revise and complete the catalogues of hypocenters and intensities. Upon the recommendation of CERESIS the catalog of the Programa para la Mitigación de los Efectos de los Terremotos en la Región Andina (SISRA) was extended until 1991 for earthquakes of magnitude mb greater than or equal to 3.0 and, concerning intensities, with the aim of including all those felt.

In August 1993 we began the revision of the archives of the Casa de la Moneda in Potosí and in the Archivo Nacional in the city of Sucre. The history of Bolivian seimicity has been improved; several earthquakes felt in Potosí previously were not catalogued: 22 February 1662; 26 February 1678; September 1720; 2 September 1743; July 1747; 1793. Another earthquake occurred in 1873 in the city of Sucre.

Finally, six seismogenic zones in Bolivia have been distinguished:
1. In the zone of Consata-Mapiri, in the north of the Departamento of La Paz, the seimic activity is of shallow and intermediate depth. The largest shallow earthquake has been of magnitude 6.2 and of modified Mercalli intensity VIII, on 24 February 1947.
2. In the central zone of Bolivia, behind the Arica "elbow", in the Departamentos of Cochabamba, Chuquisaca and Santa Cruz, the seismic activity is of shallow depth. It may be subdivided into three sections: a. between Cochabamba and the Provinces of Chapare and Carrasco, being the largest earthquake of mb 5.6, of MM intensity VI-VII, on 9 May 1986; b. southsouthwest of Santa Cruz City, being the largest earthquake of mb 5.9 and MM intensity VII, on 26 August 1957; c. the area between Arque and Aiquile, with the largest earthquake of mb 5.9, MM intensity VII, on 1 September 1958.
3. Sucre-Tinquipaya has shallow seismic activity. The largest earthquake has been of magnitude 6.1 of MM intensity VII, on 28 March 1948; it caused extensive damage in Sucre, the capital of Bolivia.
4. In the zone of the deepest earthquakes, Santa Cruz-Yacuiba, the magnitudes are in the range of 4.5 to 6.0.
5. In the zone Yacuiba-Tartagal, shared between southern Bolivia and northern Argentina, the seismic activity generally is of shallow depth. The largest earthquakes have been of magnitude 6.4 and of MM intensity VII-VIII, on 23 September 1887 and 23 March 1899.
6. In the subduction zone, extending into southern Peru and northern Chile, there are intermediate depth earthquakes. On 17 May

1909 an earthquake of magnitude 5.2 was felt with MM intensity VI.

Vega (1980), using the instrumental catalogue of earthquakes of Bolivia from 1913 to 1976 and isoseismal maps, was able to calculate the maximum accelerations which would have been felt at each point of a 1° x 1° geographic grid over the territory of Bolivia, caused by each one of the earthquakes of the catalogue that he considered. The earthquakes he used covered the latitudes 10° to 24° S and the longitudes 60° to 73° W, and, for each point of the grid, he considered the earthquakes which had occurred within a space with sides of one geographic degree. Once he had calculated the accelerations, in percentages of the acceleration of gravity for each point of the grid, by linear regression, he determined the constants of the mean annual frequency of occurrence of the accelerations N(A):

$$\log N(A) = \log \beta - \gamma \log A$$

Knowing the value at each point, he was able to define the seimic risk as:

$$R(T,A) = 1 - \exp(-N(A).T)$$

for a risk period T. He made a provisional seismic zonation of Bolivia by determining the probable maximum intensities for a period of T = 100 years, which is approximately the return period of the largest earthquakes in Bolivia, by use of the formula:

$$I(\beta, T, \gamma) = 4.4750 + 3\gamma(\log \beta + \log T)$$

(Castano, 1977; Epstein and Lomnitz, 1966; Grases, 1989a; 1989b; Lomnitz, 1974, p. 88). Cabré and Vega (1993) continued this work, calculating probabilities of exceedance of an acceleration of 0.05 g in 50 years for the grid of Bolivia and the probabilities of the occurrence of an earthquake of magnitude 5.5 within 30 years. With the improvement of the earthquake catalogue for Bolivia, we are also continuing this work.

Use of ancient seismograms

We have found the response curves of the seismographs that operated at La Paz the years 1913 to 1962, thus revealing a considerable amount about world, and especially South American, seismicity. "Data for the southern hemisphere were much improved by the establishment of the station at Riverview (near Sydney), Australia, beginning March 18, 1909.... A further improvement followed the installation at La Paz (Bolivia), with reports beginning May 1, 1913. La Paz at once became, and still remains, the most important single seismological station of the world. This

is a consequence of its isolated location, the sensitive instruments, and the great care with which records were interpreted and reports issued under the direction of Father Descotes" (Gutenberg and Richter, 1954, p.6); in 1962, LPB, the World-Wide Standard Seismograph Network became operational.

For the three seismographs recording on smoked paper, dynamic magnification equals $V/D^{1/2}$, where V is static magnification and

$$D = [1 - (\frac{T}{T_o})^2]^2 + \frac{4 \ln^2 \epsilon}{\pi^2 + \ln^2 \epsilon} (\frac{T}{T_o})^2$$

T being the ground period, $T_o$ the period of the seismometer, $\epsilon$ the damping ratio and ln the logarithm to the base e. V, $T_o$ and $\epsilon$ are given in the La Paz Boletín Sísmico; $r/T_o^2$, the solid (or pen) friction, is also given, but its effect, except for very large pen movement, is included in the damping ratio $\epsilon$ (Sohon, 1932, p. 63 ; Byerly, 1933; 1942, p. 110). At a period of 12 s, the dynamic magnification of the two horizontal seismographs recording on smoked paper was approximately 500. For the Galitzin-Wilip seismographs, dynamic magnification equals $T/C'UD^{1/2}$, where C' is $\pi L/AK$, L is the distance from the hinge to the center of oscillation of the pendulum, A is the optical lever arm of the galvanometer, K is Galitzin's 'transfer factor', U is $1+(T/T_g)^2$, $T_g$ is the period of the galvanometer, $\mu^2$ is $1-\zeta^2$, $\zeta$ is the fraction of critical damping of the seismometer and

$$D = (1 + (T/T_o)^2)^2 - 16\mu^2(T/T_o)^2$$

(Galitzin, 1911, p.266). $T_o$, $T_g$, $\mu^2$ and log C' are given in the La Paz Boletín Sísmico. At a period of 8 s, the dynamic magnification of the Galitzin-Wilip seismographs at La Paz was approximately 2000.

Engagement in GSSETT-3

The Secretary of the Ministry of External Relations of Bolivia sent the following message to the Director of Observatorio San Calixto on 26 July 1995: "I am informing you that, having analyzed the suitability of incorporating Bolivia into the International Experimental System of Seismic Monitoring, Group of Scientific Experts Technical Test 3 (GSETT-3), we have sent to the Center for Questions of Disarmament, a section of the Conference on Disarmament of the United Nations, the agreement of the Government of Bolivia to be incorporated into GSETT-3 and to assign an Alpha seismographic station.

...........

"The Center for Questions of Disarmament, in accordance with the express requirements of the United Nations, and the Embassy of the

United States, in the framework of the programs of cooperation known as the Auxiliary Seismic Net, have encouraged the Government of Bolivia to take this step, which is in accord with its traditional policy of supporting efforts favoring peace and international security. In this sense it much appreciates that you take proper note of this present information and assist in carrying it out exactly."

This letter implies that the Bolivian Government officially delegates the cooperation in seismic monitoring to the Observatorio San Calixto, especially for staffing the National Seismic Data Center for Bolivia.

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PROFESSIONAL PERSONNEL

Lawrence A. Drake, M.A., Ph.D. (Berkeley, 1971): The Propagation of

Love and Rayleigh Waves in Non-Horizontally Layered Media.
René Alcalá (Calvo), Ingeniero Electrónico.
René Rodolfo Ayala (Sánchez), Tesista, PhD, University of Strasbourg.
Jorge José Loa, Grado (física, matemáticas), Universidad Mayor de San Andrés, La Paz.
Estela Minaya (Ramos), M.S. (St Louis), Geophysics.
William R. Ott, M.S., Ph.D. (Iowa, 1978), Physics, Geology.
Willy César Quevedo (Castillo), Tesista (geomorfología), Universidad Mayor de San Andrés, La Paz.
Angel Vega (Benavídez), Diploma, Geofísica, Universidad Mayor de San Andrés, 1971.

## INTERACTIONS

Dr. Drake attended the 15th Annual Seismic Research Symposium in Vail, Colorado, 8-10 September 1993. He visited the Instituto Geofísico, Bogotá, Colombia, 7-10 October, and attended the Caribbean Conference on Natural Hazards, University of the West Indies, 11-15 October.
Ing Angel Vega attended the Coloquio Franco-Latinoamericano sobre Microzonificación Sísmica en el Estado Falcón de la República de Venezuela, 7-11 November 1993.
Dr Drake attended the 16th Annual Seismic Research Symposium at the Thornwood Conference Center, Thornwood, New York, 7-9 September 1994. He visited Dr René Van Hissenhoven of the Instituto Geofísico, Universidad Javeriana, Bogotá, Colombia, 17-21 January, 1995, and continued on to visit Professor Agustín Udías of the University of Madrid on 22 January. He attended the NATO Advanced Study Institute in Alvor, Algarve, Portugal, 23 January - 2 February, and visited the Laboratoire de Détection et Géophysique at Bruyères, south of Paris, 3-6 February. Dr Drake also attended the Segundo Coloquio de Microzonificación Sísmica at Cumaná, Eastern Venezuela, 12-14 June 1995, and stayed for the Quinta Reunión Interamericana de Cooperación, 15-16 June. Dr Drake visited Professor Susan Beck, Dr George Zandt and Professor Terry Wallace at the University of Arizona, Tucson, on his way to the 17th Annual Seismic Research Symposium in Scottsdale.
Staff from Lawrence Livermore Laboratory, California, including Dr George Zandt, have run a north-south seismic profile in Bolivia, from April 1994 to April 1995, and staff from the University of Arizona, on account of aftershocks of the recent large earthquake near Antofagasta, Chile, have run an east-west seismic profile across Chile and west-central Bolivia from April 1994 to August 1995.
Ing. Estela Minaya is acting as liaison with the experiments and data exchange of the Lawrence Livermore Laboratory, the University of Arizona and the Carnegie Institution of Washington. She studied data exchange with Dr Paul Silver and Dr John Vandecar in Washington for two weeks in the latter part of January, 1995. She attended the Seismology and Seismic Hazard Assessment program in Managua, Nicaragua, from 22 October to 3 December 1995.

Dr. Drake has participated in a "Piloto project" workshop in Bogotá, Colombia (October 17-18, 1995) in connection with the program of the European Union, coordinated by Dr Domenico Giardini in Rome, to improve the rapid location and characterization of earthquakes in South America.
The visit of Tim Ahern and Reinoud sleeman (Nov. 17-18, 1995) has facilitated the coordination for the "Piloto project".
Ing. René Alcalá participated in a "Global seismological observation" training (oriented to explosion discrimination) in Tsukuba, Japan, organized by the International Institute of Seismology and Earthquake Engineering of Tokyo (Nov. 6-Dec. 20, 1995).
Kyle Pesefield, from the Albuquerque Seismological Laboratory, has been visiting with us (Dec. 12-21, 1995) and discussing the output of LPAZ station.
Ing. Angel Vega presented "Complementos a la Historia Sísmica de Bolivia" at the III Reunión Técnica of the Instituto Panamericano de Geografía e Historia in Ciudad de México in the week (26-30 June); this meeting preceded the meeting of the International Association of Seismology and Physics of the Earth's Interior in Boulder, Colorado (in the first half of July 1995).

## FIGURE CAPTIONS

Figure 1. Profile Altiplano-Cordillera Real of P-wave velocity, S-wave velocity and density down to 40 km.

Figure 2. The normalized variation of displacement with depth of the fundamental Love modes of periods 0.7 s, 1.5 s, 5.0 s and 10.0 s for the model of the structure below Iquique.

Figure 3. Normalized variation of fundamental Love mode displacement with depth at periods of 3.5 and 2 seconds for the eastern Cordillera and the Altiplano.

Figure 4. Normalized variation of horizontal and vertical fundamental Rayleigh mode displacement with depth at period of 3.5 seconds for the Eastern Cordillera and the Altiplano.

Figure 5. Temporary short-period seismograph array Lithoscope-Bolivia, across the Andes and Altiplano. (From Aldunate, 1995).

Figure 6. Tomographic vertical profile of P-wave velocity anomalies beneath the Lithoscope-Bolivia array down to 650 km. The Nos. 3 mean negative anomaly (what increases with darkness of shading); the Nos. 4 mean that the anomaly is less than 0.5 %; the Nos. 5 mean positive anomaly. (From Aldunate, 1995).

Figure 7. The structures and continental setting of the south boundary of the Caribbean plate: a) bloque Maracaibo; b) bloque Andino of Colombia; c) bloque Bonaire; d) bloque central del Caribe

Montañoso; FDP) faja de deformación de Panamá (belt, arcuate structure); FCMS) falla marginal del Caribe Sur; CLR) Cañón los Roques; FOA) falla Oca-Ancón; FEP) falla El Pilar; GD) Golfo de Darién or Urabá; FBo) falla Bolívar; FSMB) falla Santa Marta-Bucaramanga; FB) falla Boconó; FV) falla Victoria; FLB) falla Los Bajos-El Soldado; DA) Depresión Atrato; FA) falla Atrato; FR) falla Romeral; FS) falla Salinas.
The inset is enlarged to show the multiplicity of faults in the southern tip of block Maracaibo, behind the Bucaramanga seismic nest.

Figure 8. Seismic profiles across Colombia.
a) Map showing vertical sections where hypocenters occurring at both sides within a band of 0.5° are projected (the No. 9 is 1° broad).
b) Profiles Nos. 1 to 8 are parallel to the movement of Caribbean plate relative to South American plate. Profiles Nos. 9 to 12 are parallel to the movement of Nazca plate relative also to South American plate, partly crossing the profiles Nos. 5 to 8, that is to say, a part of hypocenters are repeated in both sets of profiles. The continuity of seismic activity in the stripes 9 to 12 down to about 200 km endorses the thesis of Nazca plate being subducted beneath the Andean block down to the Bucaramanga seismic nest.

Figure 9. Permanent seismic stations in Bolivia controlled by the Observatorio San Calixto: Network around La Paz, Cochabamba (CCH), San Ignacio de Velasco (SIV) and Mochará.

Figure 10. a) Isoseismal map corresponding to the deep earthquake of June 9, 1994 (below dated June 8, according to the Bolivian time).
b) Attenuation of seismic intensity between 100 and 3000 km of distance to the epicenter. The dashed lines apply to similar earthquakes differing 0.5 in mb. (From Vega, 1994).

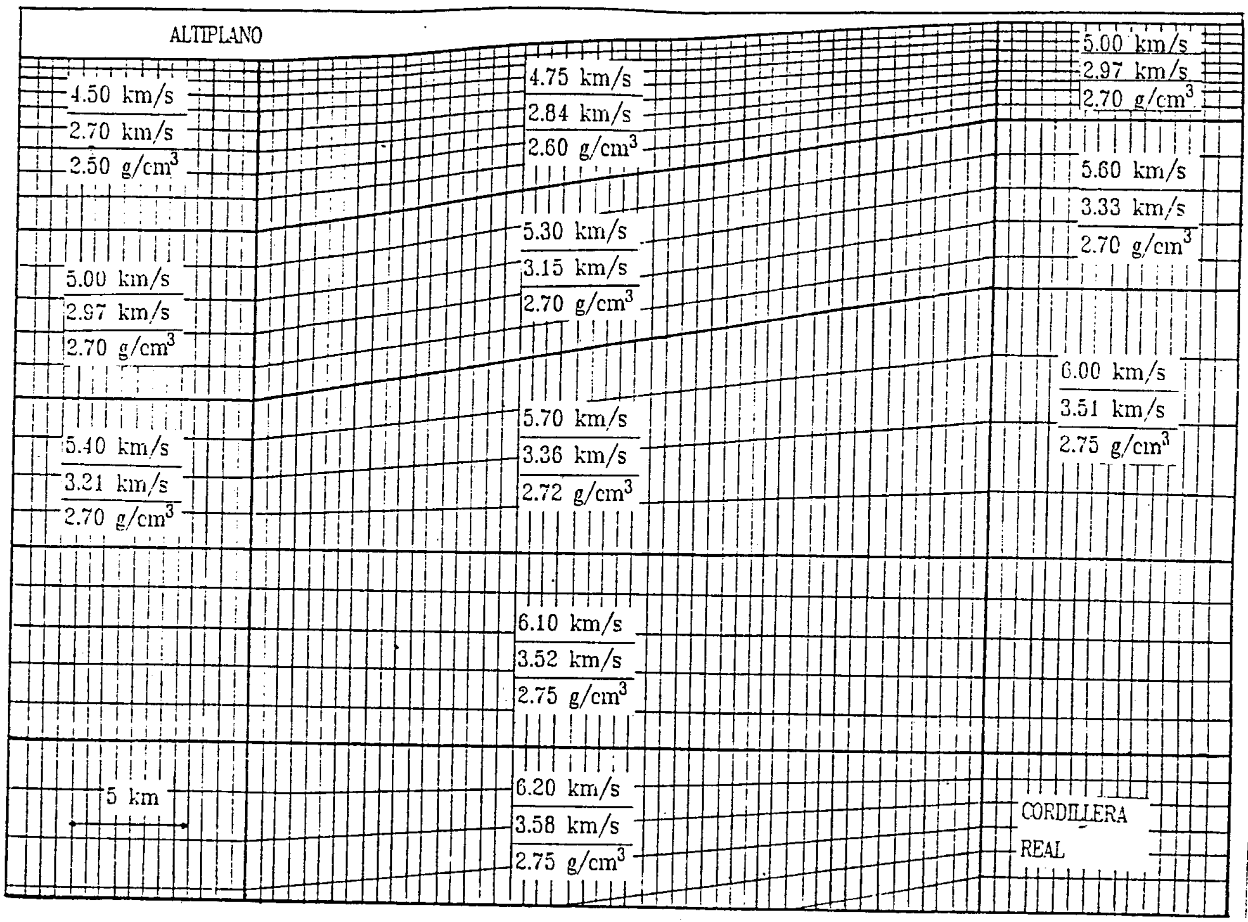



Figure 1

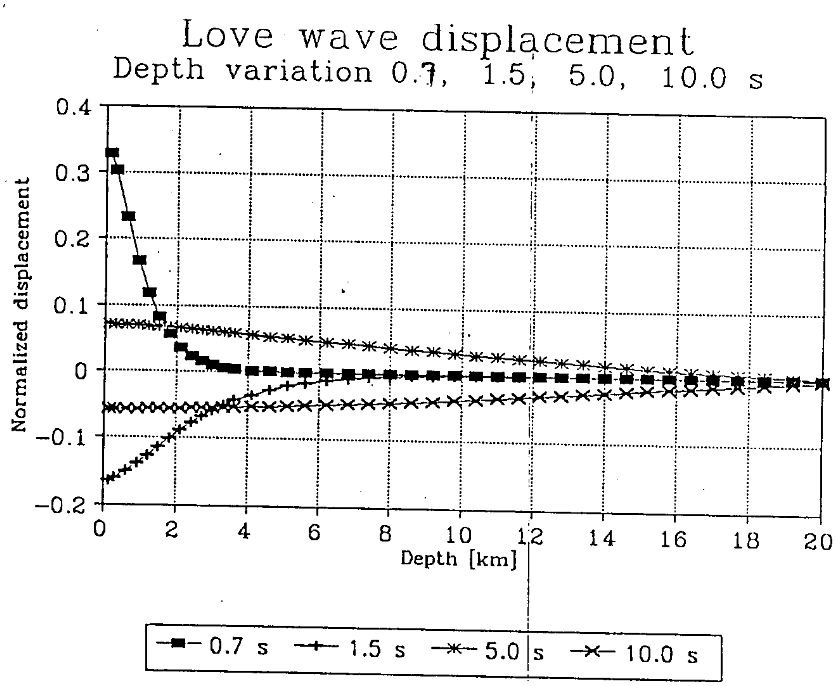



Figure 2

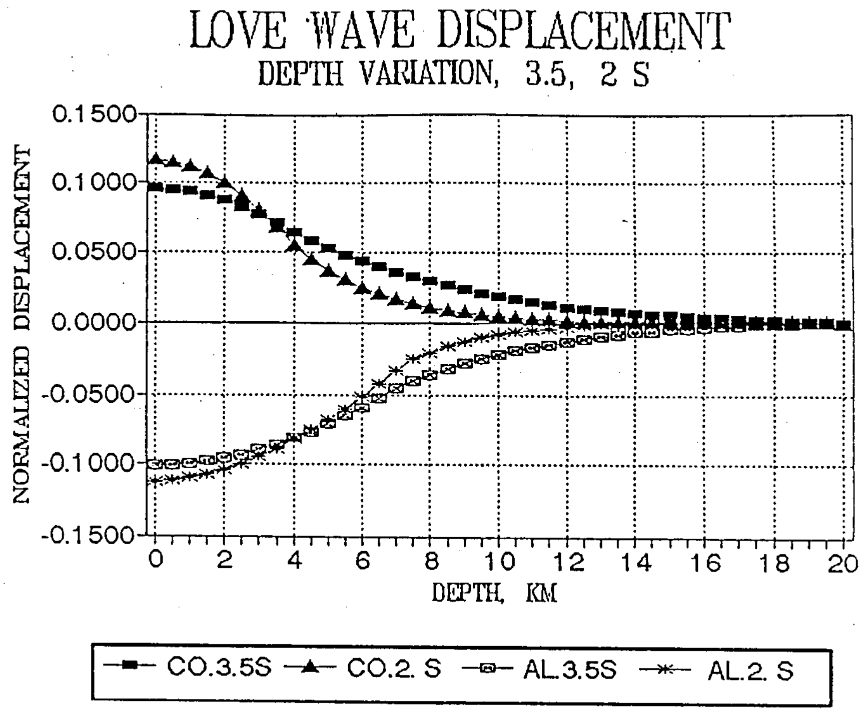



Figure 3

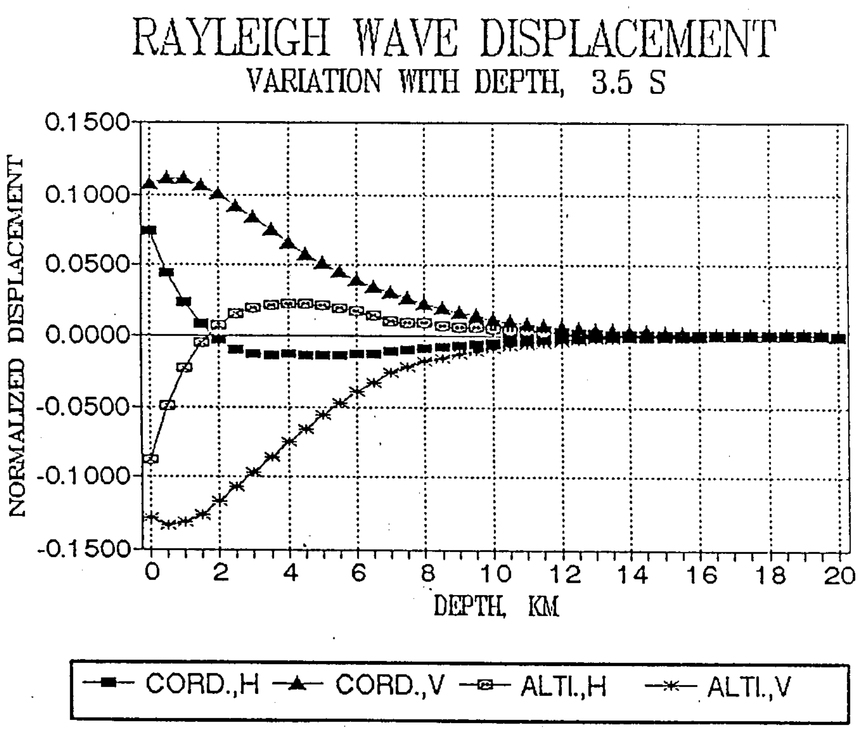



Figure 4

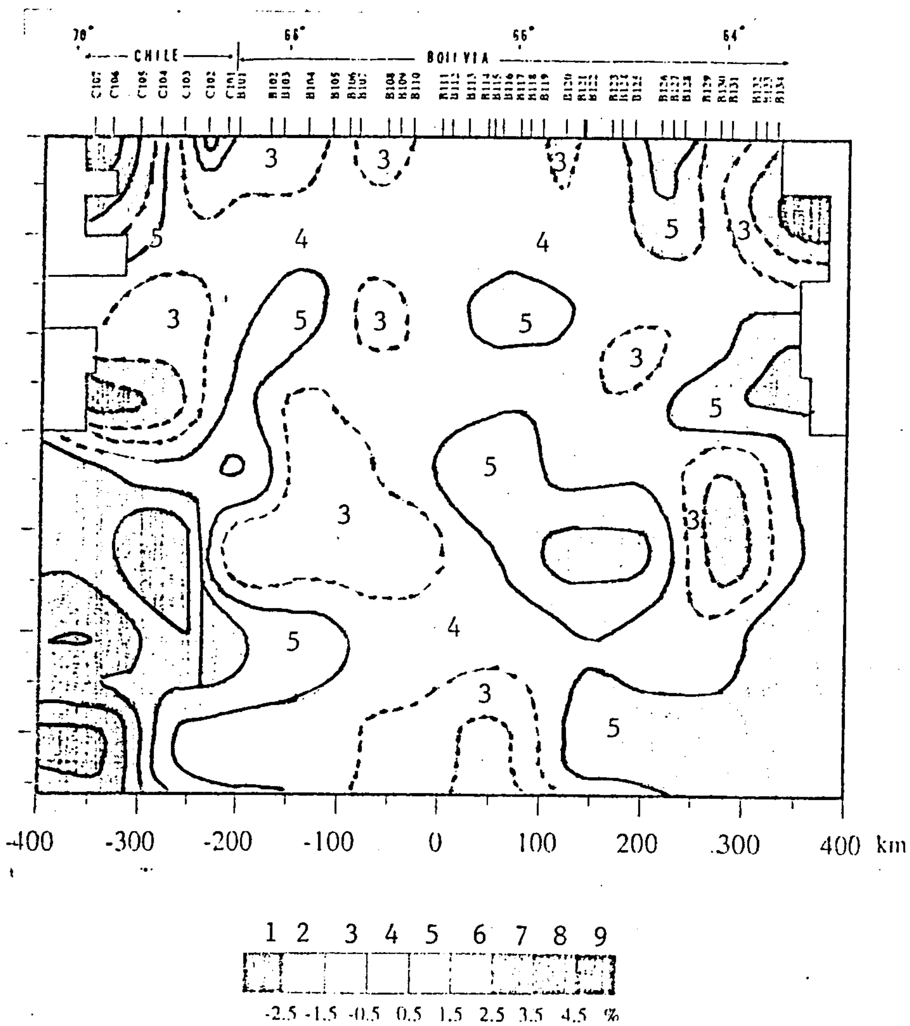



Figure 6

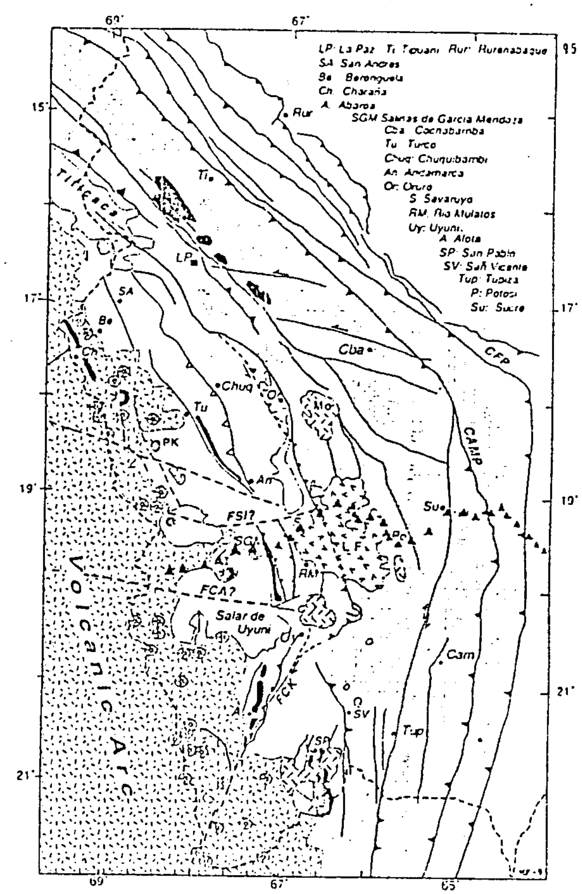
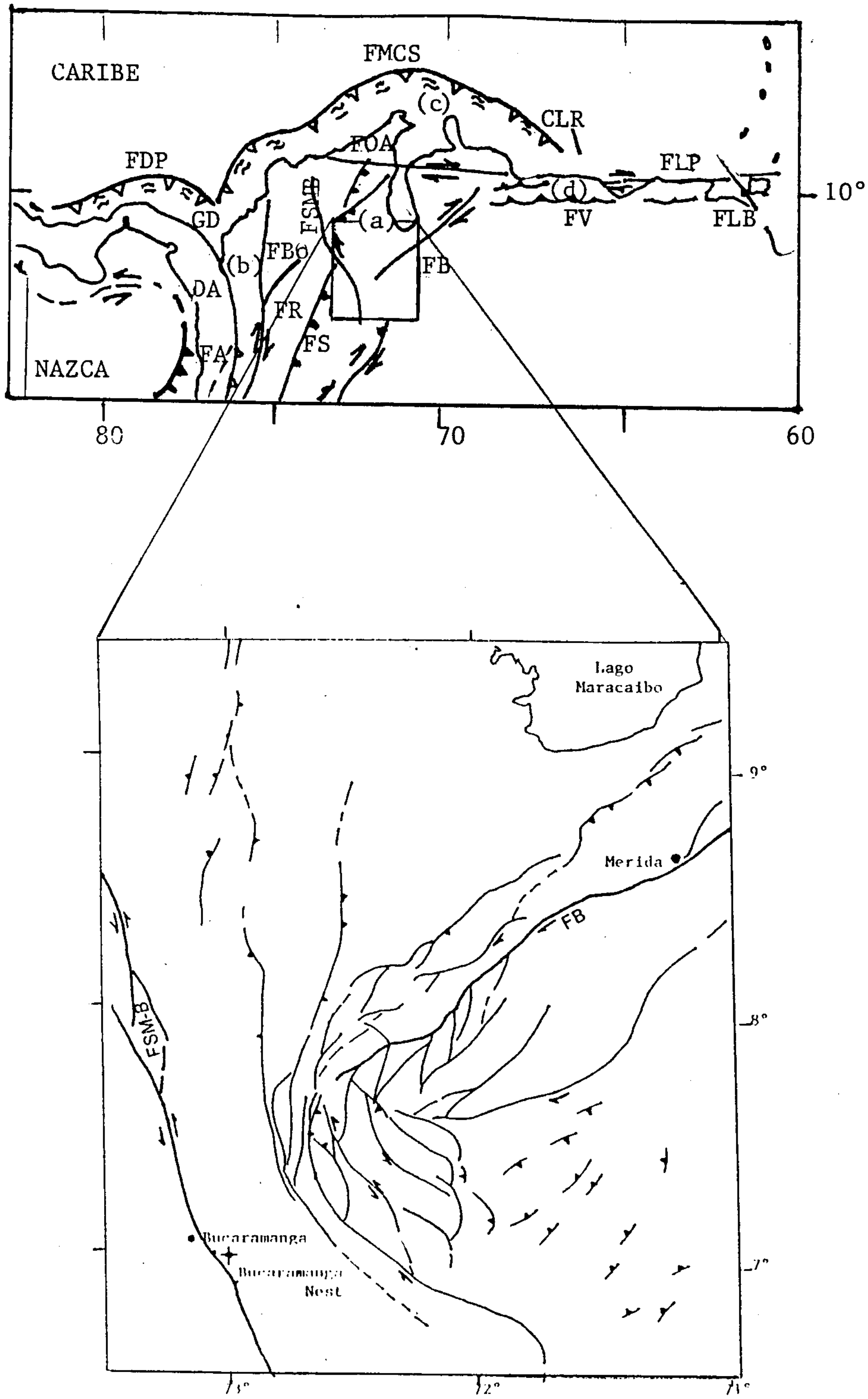



Figure 5



CARIBE
FMCS
(c)
CLR
FOA
FDP
FLP
10°
(d)
FV
FLB
GD
FSMB
(a)
(b)
FBO
FB
DA
FR
FS
FA
NAZCA
80
70
60
Lago
Maracaibo
9°
Merida
FB
8°
FSM-B
Bucaramanga
Bucaramanga
Nest
7°


Figure 7

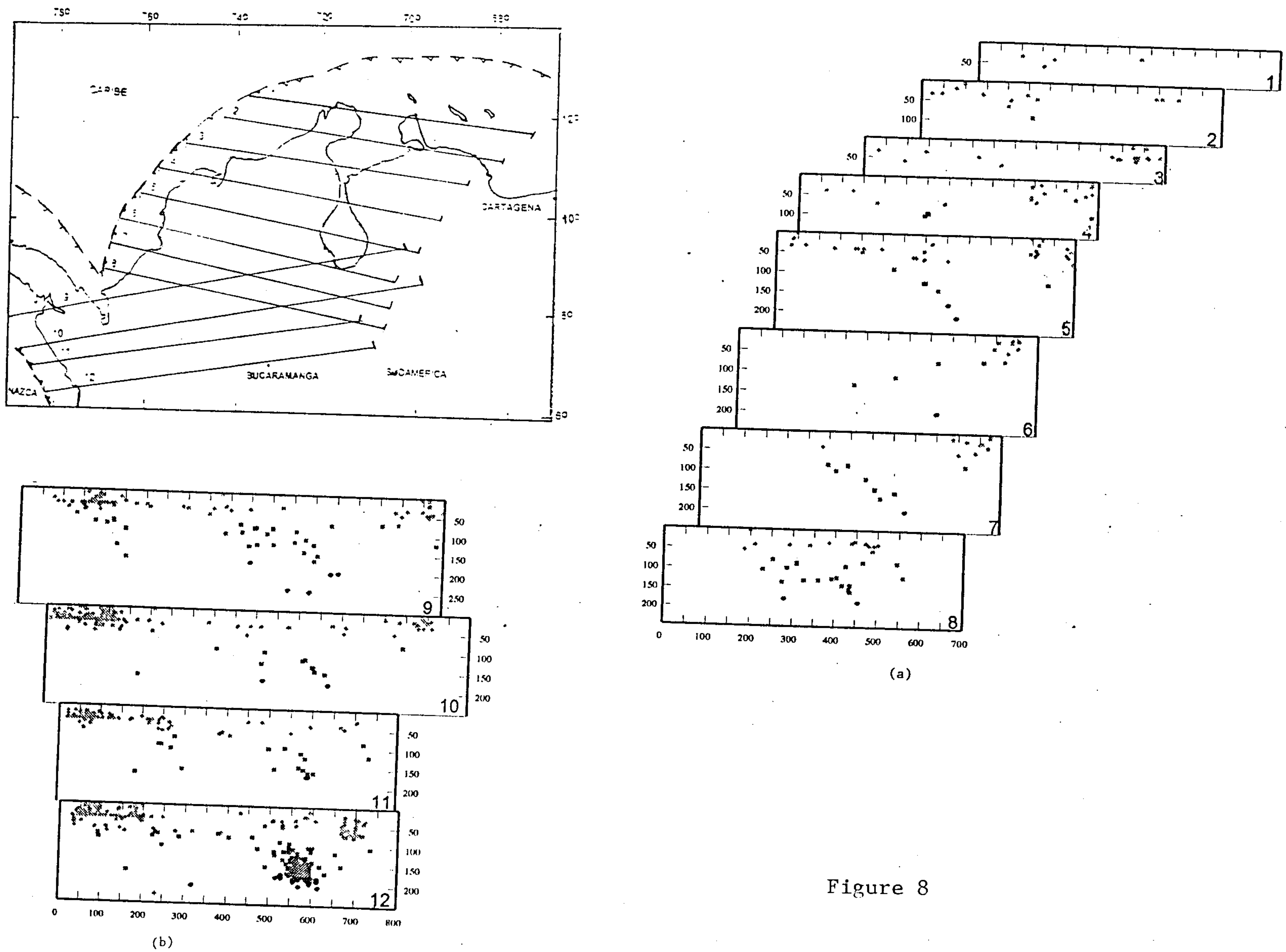



Figure 8

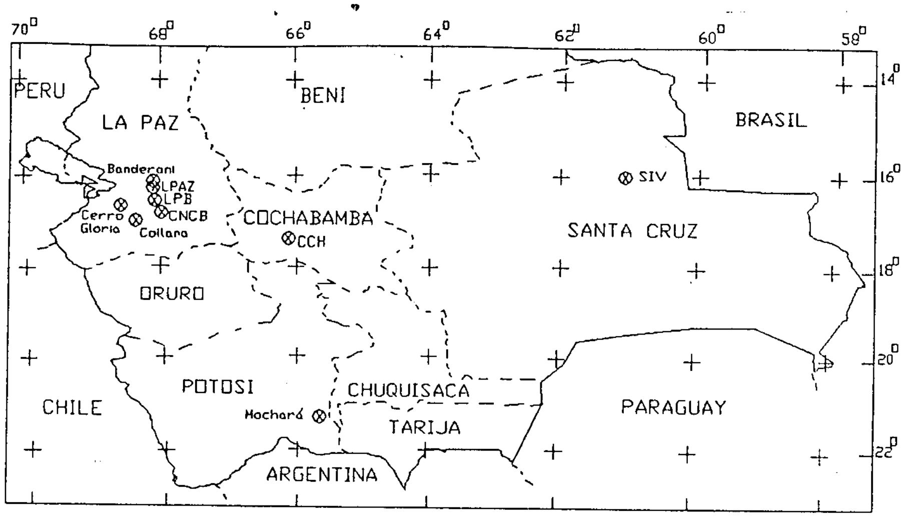
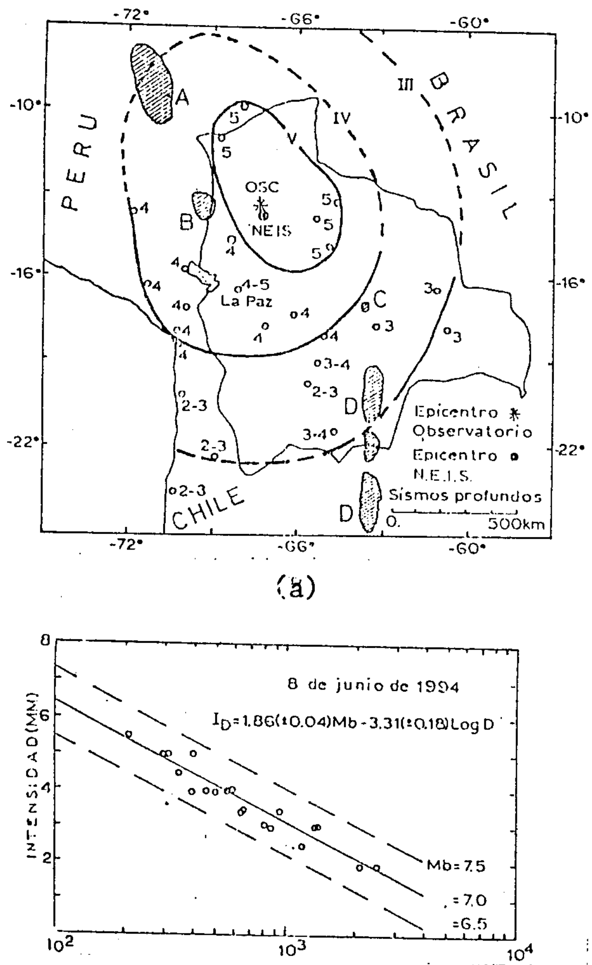



Figure 9




(b)

Figure 10